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Effect of Residual Stress on Fracture Parameters of through Cracks in Welded Plates

Rahman Seifi

Engineering College, Bu-Ali Sina University, Hamedan, Iran

Abstract

When there is residual stress in a material, stress intensity factor (SIF) in liner elastic fracture mechanics (LEFM) approach and J-integral in elastic-plastic fracture mechanics (EPFM) approach have not constant values and are path dependent parameters. In this paper, we used the modified relations for them that take into account the effects of the residual stress. These relations have constant values in existing of residual stress and are independent of the path. In this study, we investigated a butt welded plate with through thickness crack perpendicular to the weld path. The SIF and J-integral were numerically calculated for applied and residual stresses. Results have a good agreement with theoretical values obtained by weight function method. Also it was shown that the modified SIF and J-integral can be used as fracture parameters to obtain other properties of fractured plates and structures.

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Keywords: residual stress; modified J-integral; stress intensity factor; weld.

1. Introduction

Nowadays, the welded structures have major roles in industries. The final strength of the structure is dependent on the quality of welding. In the recent years, several studies were done on the integrity and health of the weldments. It was determined that the welding has some important effects on the strength of materials: the properties of the base metal on near zones of welded areas were changed. The properties of weld metal were different and weaker than the base metal. The welding process induces tension residual stresses in the weld affected zones. Different types of faults such as cracks may be created in the metal.

Residual stresses and weld defects together have critical and risky effects on the structures. Under fatigue loading, the static residual stresses change the life of components. These variations are introduced in both initiation and growth of fatigue cracks [1-3]. Also crack growth affects the residual stresses distributions [4-6]. To investigation of the crack behaviors in the residual stress fields, it is necessary to determine the major parameters of the crack such as stress intensity factors (SIF) and/or J-integral in presence of the residual stresses. For elastic materials we can use the linear elastic fracture mechanics (LEFM) approach to describe the behaviors of the cracks and to estimation of the SIFs (K) due to the residual and applied stresses [4, 5, 7]. If there is considerable plastic deformation in crack front, it is necessary to use the elastic-plastic fracture mechanics (LPFM) approach. In this situation, the crack behavior can be determined by J-integral [8-11]. Determination of the residual stress effects on crack behavior is very important. In elastic deformation, we can use the superposition approach to determine the effects of external and internal stresses. In this approach, the effects of these stresses are investigated separately [4, 5, 7, 8]. For elastic-plastic materials, superposition approach cannot be used. In this case, we must calculate the J-integral due to external loading and residual stresses simultaneously [9, 12, 13]. The results of numerical analysis show that the calculated values of K and J-integral are path dependent. Their values vary with distance from the crack front [12, 14].

In this paper, the elastic and elastic-plastic behaviors of welded plates were investigated that contain through cracks in welded regions.

2. Materials and sample

In this work, we used the mechanical properties of the OX-522D steel [5] where depicted in table (1).

* Corresponding author. Tel.: +988118257410 ; fax: +988118257400.

E-mail address: rseifi@basu.ac.ir.

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Table (1): Properties of OX-522D steel [5]

E (GPa)	207
σ_{yp} (MPa)	406
H(GPa)	18
K_{IC} (MPa $\sqrt{m}$)	90

where E is the elastic modulus, σ_{yp} is the yield stress, H is the tangent modulus and K_{IC} is the fracture toughness.

Specimens were made using butt weld and had final dimensions of 500mm*700mm. weld path was considered along the large edge. According to figure (1.a) the through crack with the length 2a was created perpendicular to the weld path.

Longitudinal residual stress due to the welding can be estimated by the following expression [5]:

$$\sigma_{yy} = \sigma_o[1-(x/c)^2]\exp(-x^2/2c^2) \tag{1}$$

where σ_o is the maximum stress in weld centerline, 2c is the wide of tension zone and x is lateral distance from weld line as depicted in figure (1.b). σ_o is always smaller than or equal to the yield stress of material. According to ref.[15], it varies with ultimate strength.

In this study, we used $\sigma_o = 340MPa$ and c=40mm from ref. [5]. 2a is the through crack length that perpendicular to weld path (figure 1.b). Crack length was varied to locate the crack tip in all three stress zones: tension, zero and compression residual stress.

In calculation of the SIFs, the elastic behavior and for J-integral calculations the bilinear elastic-plastic behavior of material were used. Through thickness variations of residual stress was ignored.

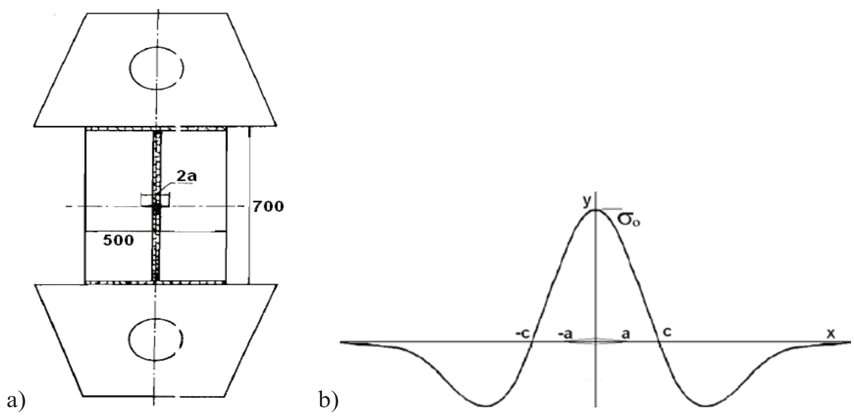


Figure 1: a) schematic view of specimen b) residual stress distribution

For this reason and because the crack is through, two dimensional analysis was used. In this study external stress was applied in weld direction (y-direction in figure 2). The applied stress was considered as $\sigma_{yy} = 200MPa$ for SIF calculations and $\sigma_{yy} = 172MPa$ for J-integral.

3. The SIFs in the residual stress fields

When there are residual stresses in the materials, effective values of SIFs (K_{eff}) are not equal to the SIFs due to the external loads only (K_{ext}). This is due to the effects of residual stresses. In LEFM, we can use the principle of superposition on calculation of the SIFs. So the effective SIF is equal the SIF due to the external load plus the SIF for residual stresses (K_{res}) [5, 7]:

$$K_{eff} = K_{ext} + K_{res} \tag{2}$$

where K_{ext} can be calculated simply by the relation $K_{ext} = f(\frac{a}{w})\sigma_{ext}\sqrt{\pi a}$. K_{res} can be estimated by weight function method [16]:

$$K_{res} = \int m(x,a)\sigma_{res}(x)dx \tag{3}$$

where σ_{res} is the residual stress distribution. $m(x,a)$ is the weight function that is independent of the loading and for mode I is given as:

$$m(x,a) = \sqrt{\frac{a}{\pi(a^2 - x^2)}} \tag{4}$$

Substitution of equations 1 and 3 into 4 gives the following relation for K_{res} :

$$K_{res} = \sigma_o\sqrt{\pi a}\exp(-0.42\alpha^2)(1-\alpha^2/\pi) \tag{5}$$

where $\alpha = a/c$. The results of this equation has maximum of 0.5% error [16].

4. J-integral calculation

With plastic deformation, the LEFM cannot be valid and the EPFM must be used. In this approach, J-integral was the important parameter that could be calculated. The local value of the strain energy release rate in a sample point (s) can be written as:

$$J(s) = \lim_{\Gamma\to 0}\int_{\Gamma}\left(Wn_1 - \sigma_{ij}\frac{\partial u_j}{\partial X_1}n_i\right)d\Gamma = \int_{\Gamma}\left(W\delta_{1i} - \sigma_{ij}\frac{\partial u_j}{\partial X_1}\right)n_i q d\Gamma \tag{6}$$

where according to figure 2, Γ is a curve (contour) surrounding the point s in a plane perpendicular to the crack front. $\vec{n}$ is a unit normal vector on Γ. W is the strain energy density. u is displacement component and q is a weight function that used to eliminate the limitation. q can be any continues function but must be unit on point s and zero on curve Γ.
If the residual and thermal stresses and body force are not considered in the material, the equation 6 can be written for 2D problem as follows:

$$J(s) = \int_A\left(\sigma_{ij}\frac{\partial u_j}{\partial X_1} - W\delta_{1i}\right)\frac{\partial q}{\partial X_i}dA \tag{7}$$

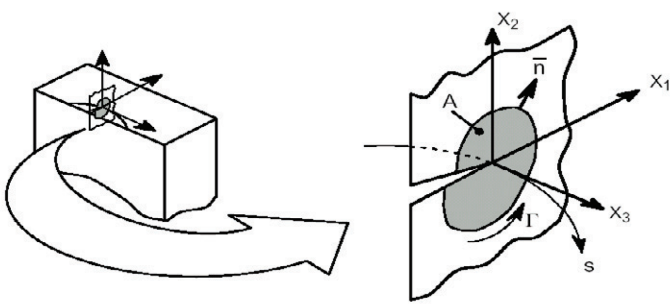


Figure 2: J-integral parameters

When there are residual stresses around the crack front, this equation is path dependent. So it cannot be used as a fracture parameter [12, 15]. There are two reasons for this subject: first, displacement gradient (strain) is not only depending on mechanical loading but also affected by initial strain due to residual stress. Second, this initial strain also changes the strain energy density (W) [13].
If initial strain due to residual stress and its strain energy density are shown with ε_{ij}^o and W^o respectively, the mechanical strain and strain energy density can be written as:

$$\varepsilon_{ij}^m = \varepsilon_{ij}^t - \varepsilon_{ij}^o = (\varepsilon_{ij}^e + \varepsilon_{ij}^p) - \varepsilon_{ij}^o \quad , \quad W = \int_0^{\varepsilon^m}\sigma_{ij}d\varepsilon_{ij}^m = W^t - W^o \tag{8}$$

where superscripts m, t, p, o refer to mechanical, total, plastic and initial components respectively.

With this definition, equation 7 can be written as [11-13]:

$$J=\int_A\left(\sigma_{ij}\left(\frac{\partial u_j}{\partial X_1}\frac{\partial q}{\partial X_i}+\frac{\partial \varepsilon_{ij}^{o}}{\partial X_1}q\right)-(W^t-W^o)\frac{\partial q}{\partial X_1}\right)dA \qquad (9)$$

This equation will be used in the following sections to calculate J-integral due to residual and external stresses.

5. Numerical Results

In this section, the numerical results for K and J-integral variations were described.

5.1 stress intensity factors (SIFs)

Because of symmetry, only one quarter of sample was modeled. Finite element model of plate with 2a=30mm through crack was depicted in figure 3. The meshes of near crack tip zones were showed clearly in figure 3b. The second-order plane stress elements were used in the model. Mid node was moved to ¼ distances from crack tip in elements that were deposited around the crack tip for creation singularity of stresses and strains.
In the LEFM approach, the relation $J=G=K^2/E$ can be used in calculation of K from J-integral results. By using this method, the SIF values for crack with a=15mm length were determined. The variations of the SIFs versus contour distance (r) from crack tip were displayed in figure 4. Results were calculated with existence of residual stress given by eq. 1. Independent variable (r) was normalized by half width (c) of tension zone and the SIFs by K_o where $K_o=\sigma_o\sqrt{\pi a}$. From this figure it can be seen that conventional values of K (K_{res}) are change with distance and not path independent. So these values cannot be used for fracture study.

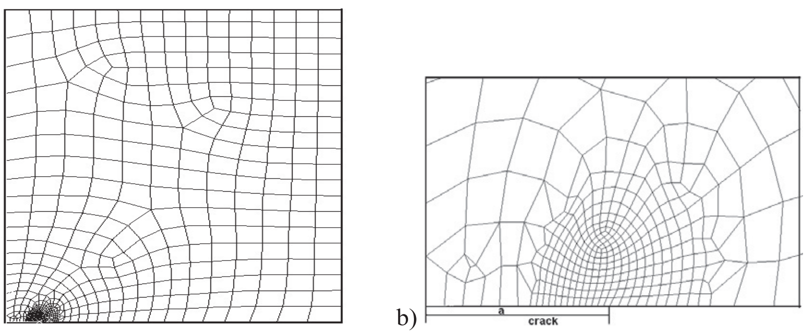
a) 

Figure 3: a)global mesh b) local mesh around crack tip

Instead, K values were calculated by using modified J-integral (K_{mdf}) have constant values and are path independent. Also these values have a good agreement with analytical (K_{ana}) values. Maximum error is about 2%. Thus, we can use the modified J-integral (eq. 9) for calculation of the SIFs in presence of residual stress fields.

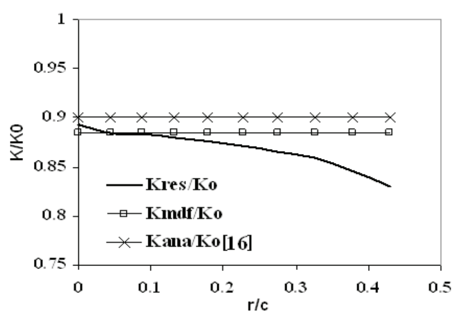


Figure 4. Variations of the SIFs with contour distance

Variations of the SIFs versus crack length due to residual stress only (RS only) and its combination with applied 200 MPa external stresses were depicted in figure 5. Again there are good agreements between analytical and numerical results.

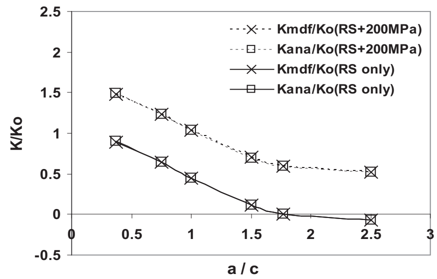


Figure 5. Effect of residual stress on the SIFs versus crack length

Existence of the crack in the body changes the distributions of stresses around the crack tip. This subject was depicted in figure 6. In this figure crack length was a=15mm and stress concentration cause that stresses arise in vicinity of crack tip. In distant from crack tip, stress distribution did not affect and residual stress didn't change considerable. Because of elastic behavior, applied stress was added to residual stress but near the crack tip due to stress concentration this summation is not important. If the material has elastic-plastic behavior, it is obviously seen that near zones of the crack due to high stresses are deformed plastically.

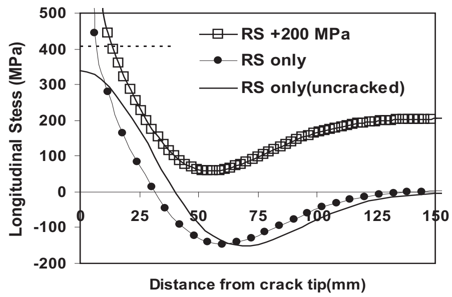


Figure 6. Stress distributions around crack tip

5.2 J-integral calculations

For study the effects of residual stress on elastic-plastic properties of crack behavior, it was assumed that material has bilinear behavior with tangent modulus of H=18GPa. The EPFM approach was used for calculation of standard and modified J-integral due to the applied and residual stresses. Path dependency of the J-integral and independency of modified J-integral (eq. 9) due to residual stress was displayed in figure 7. The values of the J-integral normalized by $J_o = (\sigma_o \sqrt{\pi a})^2 / E$ **.** Results are gathered due to the residual stress only and for take into account the effects of residual and 172MPa applied stresses. Crack length is 86.8mm.

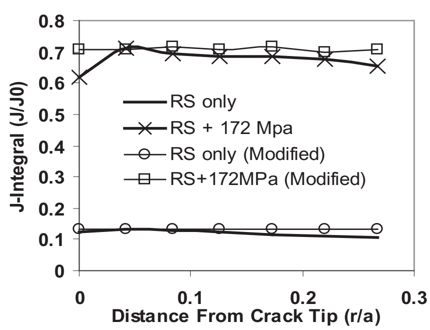


Figure 7. Variations of the standard and modified J-integral versus distance

It was seen that if applied stress is high, the path dependency of J-integral also will high. Modified J-integral has constant values independent of path in both cases.

Variation of J-integral versus crack length was depicted in figure 8. When residual stress exist, the J-integral values increased then decreased due to compressive residual stress in far field and change in near field to the tension residual stresses. These variations reduced when external load was applied on the welded plate.

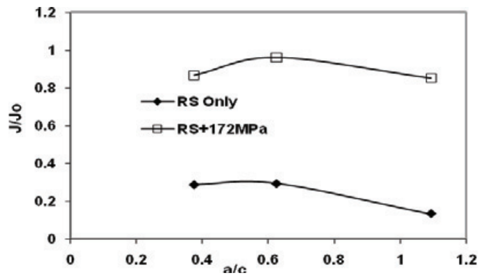


Figure 8. Modified J-integral versus crack length

6. Results

When there is residual stress in a material, the SIFs in LEFM approach and J-integral in EPFM approach have not constant values and are path dependent parameters. Modified J-integral take into account the effects of residual stress and give a path independent parameter for the crack. This parameter can be used for study of the crack behavior in all kind of stress fields. In elastic deformation, this modified J-integral also can be used for determination of the SIFs in residual stress fields. Also it was shown that the modified SIF and J-integral can be used as fracture parameters to obtain others properties of fractured structures.

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